



## DESCRIPTION

### ANGULAR VELOCITY SENSOR AND METHOD FOR DESIGNING THE SAME

5

#### TECHNICAL FIELD

The present invention relates to an angular velocity sensor having a tuning fork vibrator, and a method for designing the sensor.

10

#### BACKGROUND OF THE INVENTION

In recent years, angular velocity sensors have been used in automobiles. The angular velocity sensors particularly for this purpose have been required to be small and stable against sudden external vibrations, "disturbance" so as to have high reliability.

15

A conventional angular velocity sensor disclosed in U.S. Patent No.5438231 includes a tuning fork vibrator having a pair of vibrating arms coupled with each other at their lower ends with a coupling portion, drive electrodes formed on the vibrating arms to drive the arms in vibration directions and detection electrodes to detect the bending of the vibrating arms

20 when an angular velocity is applied to the arms. The vibrating arms are designed to have a small driving resistance so as to decrease power consumption.

25

The vibrating arms designed only for the small driving resistance may cause unnecessary vibrations when receiving vibrations as disturbance at their natural vibration frequencies different from a fundamental vibration frequency

in the vibration directions. This may cause the angular velocity sensor to output an unnecessary signal.

## SUMMARY OF THE INVENTION

5        An angular velocity sensor includes a tuning fork vibrator, a drive unit provided on the tuning fork vibrator, and a detection unit for detecting an amount of deflection of the tuning fork vibrator. The tuning fork vibrator includes a first vibrating arm having a first end and a second end and having a fundamental vibration frequency, a second vibrating arm having a first end and  
10    a second end and having the fundamental vibration frequency, and a coupling portion for coupling the first end of the first vibrating arm to the first end of the second vibrating arm. The drive unit is provided on the first vibrating arm and causes the first vibrating arm to vibrate. The drive unit has a driving resistance. The detection unit is provided on one of the first vibrating arm and  
15    the second vibrating arm, and detects an amount of deflection of the one of the first vibrating arm and the second vibrating arm when deflecting due to an angular velocity applied to the tuning fork vibrator. A ratio  $R1/R2$  is smaller than "1", where  $R1$  is the driving resistance at the fundamental vibration frequency, and  $R2$  is the driving resistance at a vibration frequency different  
20    from the fundamental vibration frequency.

This angular velocity sensor does not output unnecessary signals even if receiving disturbance.

## BRIEF DESCRIPTION OF THE DRAWINGS

25        Fig. 1A is a front view of a tuning fork vibrator of an angular velocity

sensor according to an exemplary embodiment of the present invention.

Fig. 1B is a cross sectional view of the angular velocity sensor at line 1B-1B shown in Fig. 1A.

Fig. 1C is a cross sectional view of the angular velocity sensor at line  
5 1C-1C shown in Fig. 1A.

Fig. 2 shows a driving resistance and a size of an electrode of the angular velocity sensor according to the embodiment.

Fig. 3 shows a vibration due to disturbance on the tuning fork vibrator of the angular velocity sensor according to the embodiment.

10

#### REFERENCE NUMERALS

- 1     Tuning Fork Vibrator
- 1a    Vibrating Arm
- 1b    Vibrating Arm
- 15 1c    Coupling Portion
- 2     Drive Unit
- 3     Detection Unit

#### DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

20     Fig. 1A is a front view of an angular velocity sensor according to an exemplary embodiment of the present invention. The angular velocity sensor includes tuning fork vibrator 1. Tuning fork vibrator 1 is made of a rigid material, such as silicon, and includes vibrating arms 1a and 1b which are parallel to each other, and coupling portion 1c for coupling lower end 101a of  
25 arm 1a to lower end 101b of arm 1b. Vibrating arm 1a has two drive units 2

formed thereon and has detection unit 3 formed between drive units 2. Vibrating arm 1b has detection unit 13 formed thereon and has monitor unit 4 and dummy electrode 8 which are parallel with detection unit 13.

Fig. 1B is a cross sectional view of the angular velocity sensor at line 1B-1B shown in Fig. 1A. Each of drive units 2 includes drive electrode 2A formed on vibrating arm 1a, piezoelectric layer 2B formed on drive electrode 2A, and drive electrode 2C formed on piezoelectric layer 2B. Drive units 2 extend in a direction from lower end 101a to upper end 102a of vibrating arm 1a. Detection unit 3 includes detection electrode 3A formed on vibrating arm 1a, piezoelectric layer 3C formed on detection electrode 3A, and detection electrode 3B formed on piezoelectric layer 3C. Detection electrode 3B extends in the direction from lower end 101a to upper end 102a of vibrating arm 1a. Detection electrode 3B has a length substantially equal to that of drive electrode 2C.

Detection unit 13 includes detection electrode 13A formed on vibrating arm 1b, piezoelectric layer 13C formed on detection electrode 13A, and detection electrode 13B formed on piezoelectric layer 13C. Monitor unit 4 includes monitor electrode 4A formed on vibrating arm 1b, piezoelectric layer 4B formed on monitor electrode 4A, and monitor electrode 4C formed on piezoelectric layer 4B. Dummy unit 8 includes dummy electrode 8A on vibrating arm 1b, piezoelectric unit 8B on dummy electrode 8A, and dummy electrode 8C on piezoelectric unit 8.

Coupling portion 1c has connection electrodes 5 formed thereon for connecting the electrodes of drive units 2, detection unit 3, and monitor unit 4 with outside.

A voltage is applied between drive electrodes 2A and 2C of drive units 2 which causes vibrating arm 1a to vibrate in X-axis direction 6, thereby causing vibrating arm 1b to resonate with this vibration and to vibrate at the same frequency as vibrating arm 1a. Monitor electrodes 4A and 4C of monitor unit 4  
5 output signals corresponding to the amplitudes of the vibrations of vibrating arms 1a and 1b. These signals are fed back to a control circuit which controls the driving voltage to be applied to drive electrodes 2A and 2C. Based on the signals which are fed back, the control circuit controls the frequencies, voltages, and phases of the signals to be applied to drive electrodes 2A and 2C so as to  
10 maintain the vibration of vibrator 1. Vibrating arm 1a deflects in the Z-axis direction due to a Coriolis force produced by an angular velocity applied to vibrator 1 around the Y axis, and detection electrodes 3A and 3B of detection unit 3 accordingly output a signal indicating the amount of the deflection of vibrating arm 1a which corresponds to the Coriolis force. Similarly to this,  
15 vibrating arm 1b deflects in the Z-axis direction due to a Coriolis force produced by the angular velocity applied to vibrator 1 around the Y axis, and detection electrodes 13A and 13B of detection unit 13 accordingly output a signal indicating the amount of the deflection of vibrating arm 1b which corresponds to the Coriolis force.

20 The angular velocity sensor has driving resistance  $R_d$ , a transfer impedance in driving vibrator 1. Driving resistance  $R_d$  is defined as the ratio  $V_d/I_m$  of voltage  $V_d$  applied between drive electrodes 2A and 2C to current  $I_m$  generated in monitor electrodes 4A and 4C due to the vibration of vibrator 1. In the angular velocity sensor of the embodiment, vibrating arms 1a and 1b of  
25 tuning fork vibrator 1 and drive units 2 are designed based on the ratio  $R_1/R_2$  of

value  $R_1$  of driving resistance  $R_d$  at a fundamental vibration frequency of vibrating arms 1a and 1b in vibration direction 6 to value  $R_2$  of driving resistance  $R_d$  at a disturbance vibration frequency different from the fundamental vibration frequency. That is, in designing the angular velocity sensor, the sizes of vibrating arms 1a and 1b and drive units 2 are determined based on the ratio  $R_1/R_2$ .

Fig. 2 shows the relation between the ratio  $D/L$  (represented by the horizontal axis) of length  $D$  of each of drive electrodes 2A and 2C to length  $L$  of each of vibrating arms 1a and 1b, and the ratio  $R_1/R_2$  (represented by the vertical axis) of driving resistances  $R_d$ . As shown in Fig. 2, the relation between these ratios is similar to a quadratic curve having a minimum value.

Vibrating arms 1a and 1b vibrate at natural vibration frequencies in different modes. At the fundamental vibration frequency of value  $R_1$  of driving resistance  $R_d$ , the vibration has only one node positioned at lower end 101a.

Fig. 3 shows the vibration acting on the tuning fork vibrator according to the embodiment at a disturbance vibration frequency corresponding to value  $R_2$  of the driving resistance, which has been mentioned above. Value  $R_2$  of the driving resistance corresponds to the vibration at a frequency that may cause vibrating arms 1a and 1b to bend at an intermittent point in direction 6, out of the natural vibration frequencies of vibrating arms 1a and 1b. More specifically, the vibration on vibrating arm 1a has nodes at lower end 101a of vibrating arm 1a and at point 103a between lower end 101a and upper end 102a of vibrating arm 1a at the disturbance frequency of value  $R_2$  of the driving resistance, while the vibration on vibrating arm 1b has nodes at lower end 101b of vibrating arm 1b and at point 103b between lower end 101b and upper end

102b of vibrating arm 1b. The vibration at the disturbance frequency may often occur fewer than the vibration at the fundamental vibration frequency. This mode of the vibration at the disturbance frequency may be taken into consideration for designing the angular velocity sensor in addition to other  
5 modes, such as a mode in which both vibrating arms 1a and 1b vibrate in the X-axis direction and a mode in which both arms 1a and 1b vibrate in the Z-axis direction, so as to improve the reliability of the angular velocity sensor.

The ratio  $R1/R2$  is determined to be less than "1" so that vibrating arms 1a and 1b are less affected by disturbance. Therefore, in order to prevent the  
10 vibration shown in Fig.3, the ratio  $R1/R2$  is determined to be less than "1" based on Fig. 2 by determining the ratio  $D/L$  so as to satisfy the relation of  $0.38 < D/L < 0.46$ .

In the above description, attention is paid to the relation between lengths  $D$  of drive electrodes 2A and 2C and length  $L$  of vibrating arm 1a. Similarly,  
15 lengths  $D$  of detection electrodes 3A and 3B may be determined to be  $0.38 < D/L < 0.46$ .

Auxiliary weight unit 7a is preferably provided on portion 103a of vibrating arm 1a where drive units 2 or detection unit 3 is not formed thereon. Similarly, auxiliary weight unit 7b is preferably provided on portion 103b of  
20 vibrating arm 1b where monitor unit 4, detection unit 13, or dummy unit 8 is not formed thereon. The electrodes provided on vibrating arms 1a and 1b are provided by forming a base electrode on the entire surface of a silicon substrate providing tuning fork vibrator 1, and then, the base electrode is etched so as to remove an unnecessary portion thereof. This etching may damage a surface of  
25 the silicon substrate, thereby changing properties of the angular velocity sensor.

However, auxiliary weight units 7a and 7b reduce an exposing surface of vibrating arms 1a and 1b, thereby preventing the properties of the angular velocity sensor from changing. The same unit may be applied to the etching of the piezoelectric layers.

5        Fig. 1C is a cross sectional view of the angular velocity sensor at line 1C-1C shown in Fig. 1A. Similar to drive units 2 and detection unit 3, auxiliary weight unit 7a formed on vibrating arm 1a includes electrode 107A formed on vibrating arm 1a, piezoelectric layer 107C formed on electrode 107a, and electrode 107B formed on piezoelectric layer 107C. Similar to monitor unit  
10    4 and detection unit 13, auxiliary weight unit 7b formed on vibrating arm 1b includes electrode 207A formed on vibrating arm 1b, piezoelectric layer 207C formed on electrode 207a, and electrode 207B formed on piezoelectric layer 207C. Auxiliary weight units 7a and 7b have the same structure as drive units 2, detection unit 3, monitor unit 4, and detection unit 13, thereby allowing all of  
15    these units to be formed simultaneously without any additional process. Auxiliary weight unit 7a is separate from drive units 2 and detection unit 3, while auxiliary weight unit 7b is separate from monitor unit 4, detection unit 13, and dummy unit 8.

      Detection electrode 3B of detection unit 3 may have a length equal to that  
20    of drive electrode 2C of drive units 2 so as to align end surface 3D with end surface 2D. This allows end surface 307a of auxiliary weight unit 7a facing end surfaces 3D and 2D to be straight, thereby decreasing the exposing surface of vibrating arm 1a. Similarly, detection electrode 13B of detection unit 13 may have a length equal to that of monitor electrode 4C of monitor unit 4 and  
25    that of electrode 8C of dummy unit 8 so as to align end surface 13D with end



surfaces 4D and 8D, so that end surface 307b of auxiliary weight unit 7b facing end surfaces 13D, 4D, and 8D can be straight, thereby decreasing the exposing surface of vibrating arm 1b.

Auxiliary weight units 7a and 7b lower the fundamental vibration  
5 frequencies of vibrating arms 1a and 1b. Vibrating arms 1a and 1b may be preferably shorter or wider in order to obtain a predetermined fundamental vibration frequency. That is, auxiliary weight units 7a and 7b, providing the predetermined fundamental vibration frequency, allow vibrating arms 1a and 1b to be short, thereby reducing the size of the angular velocity sensor, or allows  
10 arms 1a and 1b to be wide, thereby increasing the areas of drive units 2 and detection unit 3 formed thereon and improving the efficiencies in driving and detection.

The shape of auxiliary weight unit 7a may be adjusted by trimming with a laser so as to control the weights or the centers of gravity of vibrating arms 1a  
15 and 1b. This operation accordingly controls a vibration frequency and a vibration direction, thereby providing a precise angular velocity sensor generating less noise.

In the vibrator 1 according to the present embodiment, drive units 2 are formed exclusively on vibrating arm 1a of the two vibrating arms 1a and 2b,  
20 thereby exclusively driving vibrating arm 1a. Vibrating arm 1b may preferably have a structure symmetrical to that of vibrating arm 1a in order to have the same resonance frequency as vibrating arm 1a. Dummy unit 8 provides vibrating arm 1b with a structure symmetrical to that of vibrating arm 1a.

25 In the angular velocity sensor according to the present embodiment, drive

units 2 exclusively drive vibrating arm 1a. However, vibrating arm 1b may be driven together with vibrating arm 1a by at least one of dummy unit 8 and the monitor unit, which have the same structure as drive units 2.

In the angular velocity sensor according to the present embodiment, the  
5 length of drive electrode 2A at the uppermost position in drive unit 2 is determined based on the length of vibrating arm 1a. Piezoelectric layer 2B and drive electrode 2C may have lengths equal to or greater than drive electrode 2A. Only a region in piezoelectric layer 2B of drive unit 2 on which drive electrode 2A is formed and to which a voltage is applied contributes to the driving.  
10 Therefore, the length of drive electrode 2A at the uppermost position determines an effective area of piezoelectric member 2B so as to obtain desired properties.

#### INDUSTRIAL APPLICABILITY

An angular velocity sensor according to the present invention reduces  
15 noise due to disturbance, and hence is useful for cases in which the sensor is mounted on vibrating bodies, such as automobiles.